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# Mechanical Property Across Size Scales: 3D Printed Metal Materials with Microscale Heterostructures


Chinese Aeronautical Establishment

（CAE）

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# 3D Printed Aeronautical Materials

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| | |
|---|---|
| Background | 3D printing provides high-performance aeronautical materials |
| Progress | 3D printing generates size effects due to the micro heterostructures |
| Result | Size effects provide high strength and ductility but also analysis difficulty |
| Prospect | Fatigue and structural integrity of printed materials needs more research |

# Background

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## □ 3D printing provides high-performance aeronautical materials

| | |
|---|---|
| Vertical stabilizer part of A350WXB, *EOS Inc.* | Fuel nozzle of LEAP engine, *GE* |
| Antenna bracket of RUAG satellite, *EOS Inc.* | Turbine blades made by EBM, *GE* |


Traditional manufacturing is unable to build such structures or needs much more time, weight, and costs.

# ☐ Advantage of 3D printing aeronautical materials

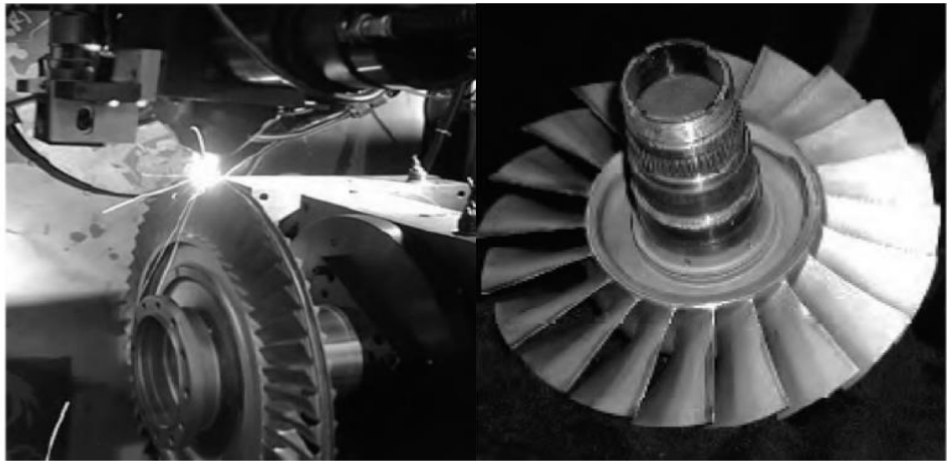
**1. Lower weight, higher performance**

AM allows finer geometric optimization, providing structures with higher performance and lower weight.

**2. Less parts and assembles**

AM decreases assembling work thus saves much time and cost, and reduces further testing.

Printed Titanium part of A350XWB



AM repaired turbine blades, *Optomec Inc.*

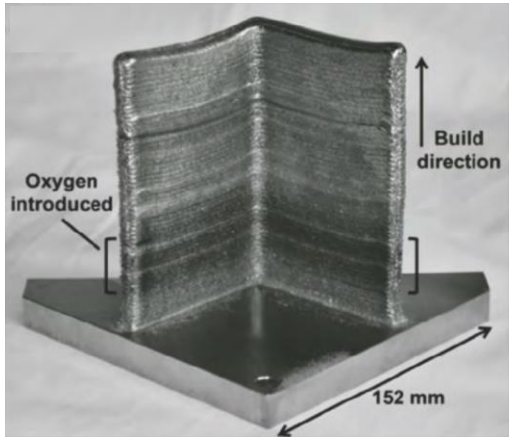
**3. Structural repairing**

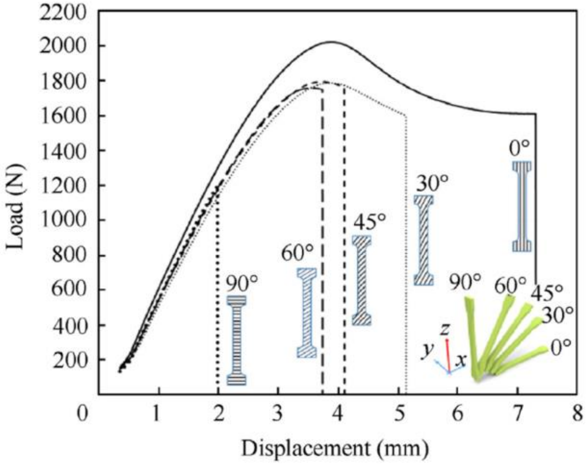
The strength of the AM repaired structure is no less than the original one.

**4. Design for addictive manufacturing**

Material-Structure-Function integrated design; force, thermal, electromagnetic, etc. integrated design; DfAM and DfAAM.

## Difficulty and potentiality of 3D printing: Heterostructures

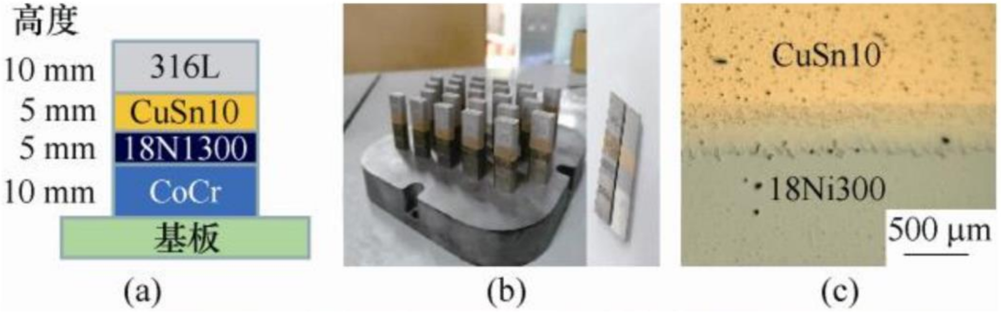


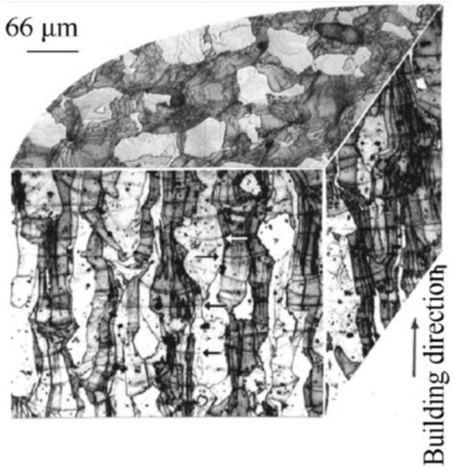

Ti6Al4V alloy (DED), Carroll, 2015 (Left)

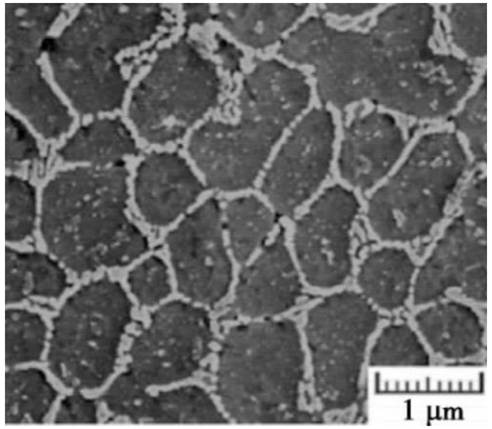
Uniaxial property of different printing angle (SLM), Yang, 2018 (Right)

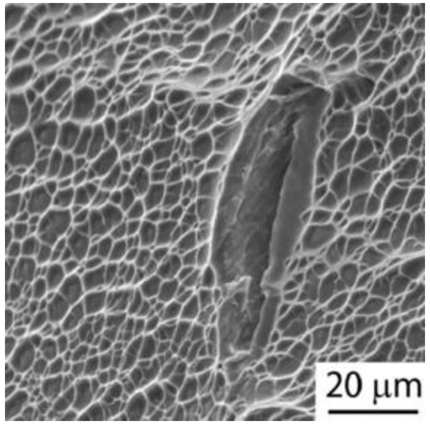
Multi-phase printing




Graded functional material (SLM), Yang, 2019




17-4PH stainless steel (SLM), Murr, 2012 (Right)

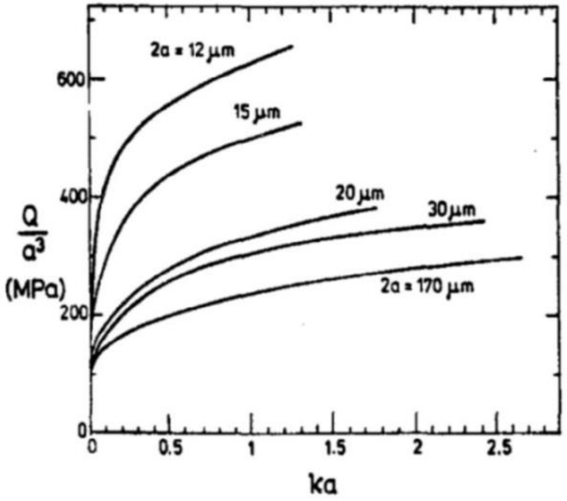
AlSi10Mg alloy (SLM), Fousova, 2018 (Left)

# ☐ Mechanical features: Size-Effect

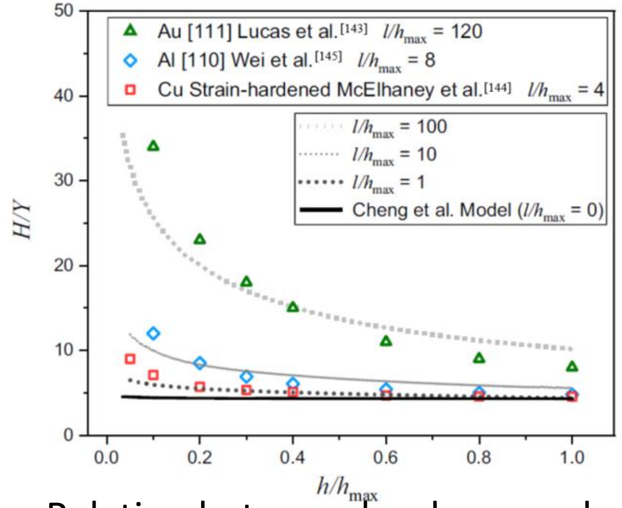
Size-effect exists in most materials, especially significant in materials with a characteristic size below millimeters, which always exists in AM materials.

In many experiments, the AM materials have been found higher strength and hardness, but lower fatigue performance.

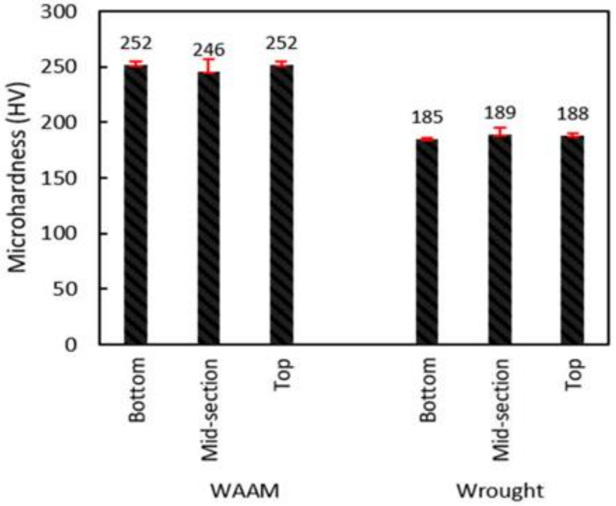
This High strength – Low ductility feature coincide with the material size effect.



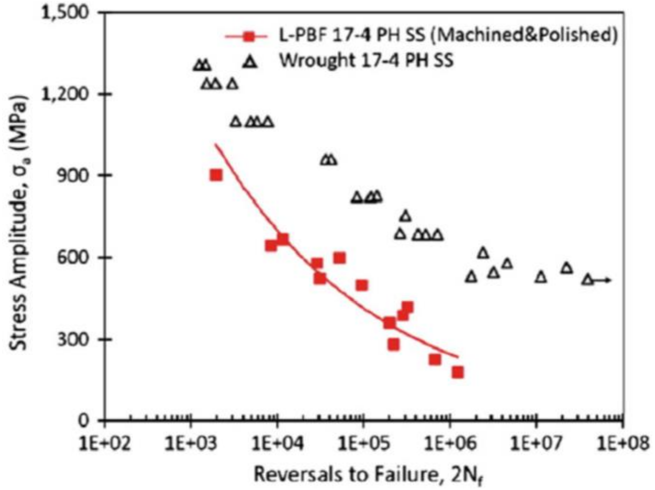

Relation between torsional stiffness and wire diameter, Fleck, 1994




Relation between hardness and indentation depth, Yu, 2022

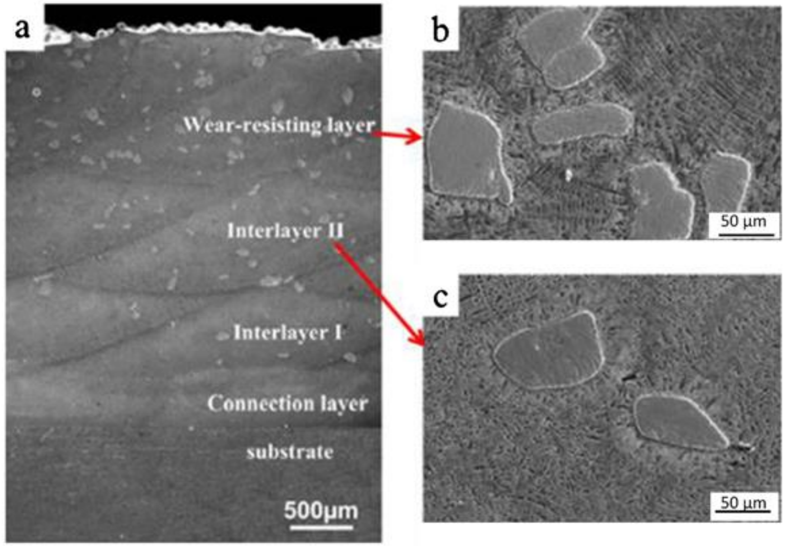



Hardness of WAAM and wrought IN718, Bhujangrao, 2020

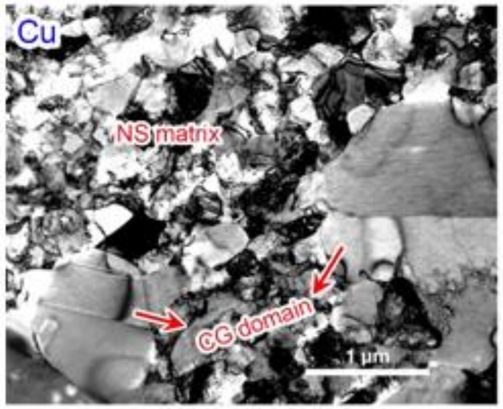



Fatigue properties of AM and wrought 17-4PH stainless steel, Yadollahi, 2017

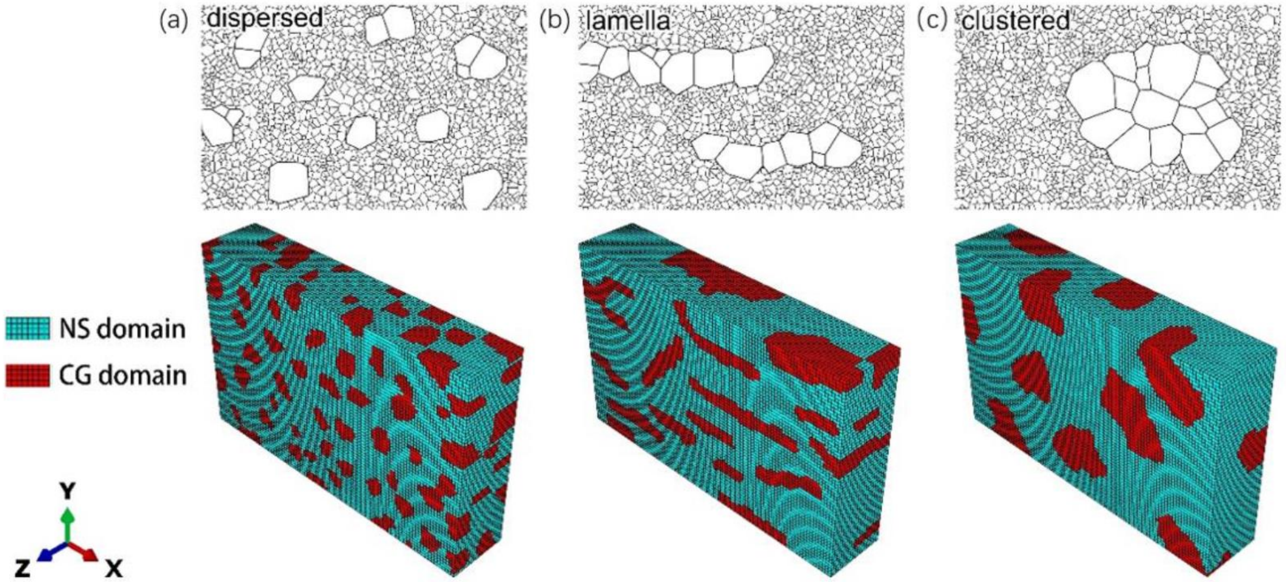
## □ Mechanical description: Model and Constitution




Micro geometry of printed interlayers. Shi, 2018




However conventional elasto-plastic theory cannot describe the size-effect of the AM heterogeneous materials.




Model describing the microscale heterostructures has been build.

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# □ Mechanical description: Model and Constitution

**CMSG** (Conventional theory of Mechanism-based Strain gradient)

$$\sigma_{flow} = M\tau \qquad \tau = \alpha\mu b\sqrt{\rho} \qquad \rho = \rho_S + \rho_G \qquad \rho_G = \bar{r}\frac{\eta^p}{b}$$

$$\sigma_{flow} = \sigma_{ref}\sqrt{f^2\left(\varepsilon^p\right) + l\eta^p} \qquad l = M^2\bar{r}\alpha^2\left(\frac{\mu}{\sigma_{ref}}\right)^2 b = 18\alpha^2\left(\frac{\mu}{\sigma_{ref}}\right)^2 b$$

With J2 flow theory

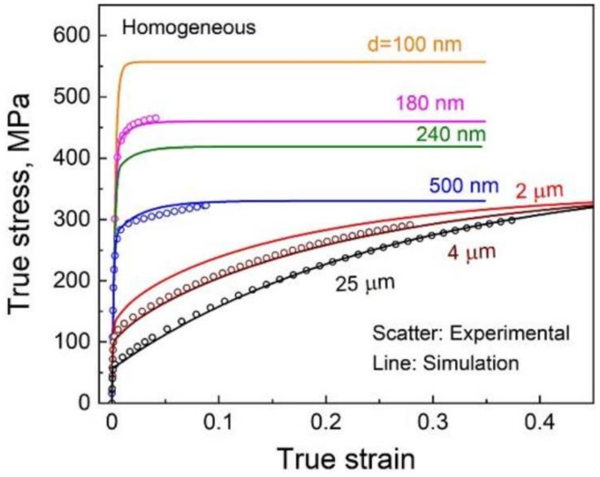
$$\dot{\sigma}_{ij} = K\dot{\varepsilon}_{kk}\delta_{ij} + 2\mu\left[\dot{\varepsilon}_{ij}' - \frac{3\dot{\varepsilon}}{2\sigma_e}\left(\frac{\sigma_e}{\sigma_{flow}}\right)^m \sigma_{ij}'\right]$$

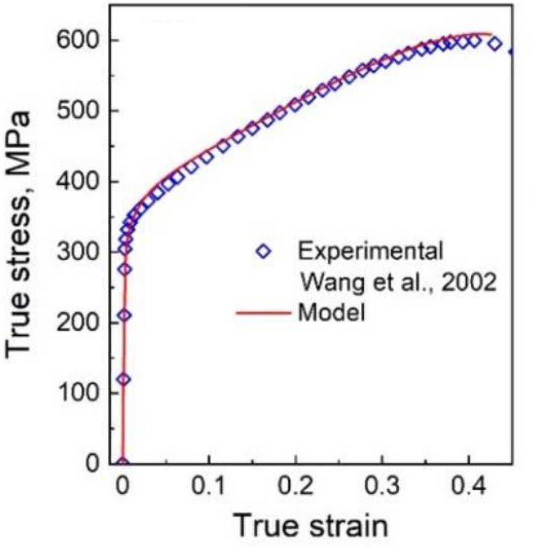
**Further Theory: Considering the long range effect of GND**

$$\sigma_{flow} = \sigma_Y + M\alpha\mu b\sqrt{\rho_{SSD} + \rho_{GND}} + \sigma_b \qquad \sigma_Y = \sigma_0 + \sigma_{GB} = \sigma_0 + \frac{k_{HP}}{\sqrt{d}}$$

$$\sigma_b = \frac{\sqrt{3}}{8}\frac{\mu b R^2}{(1-v)}\sqrt{\left(\frac{\partial\rho_{GND}}{\partial x}\right)^2 + \left(\frac{\partial\rho_{GND}}{\partial y}\right)^2 + \left(\frac{\partial\rho_{GND}}{\partial z}\right)^2}$$

$$\frac{\partial\rho_{SSD}}{\partial\varepsilon^p} = M\left(\frac{k_1}{bd} + \frac{k_2}{b}\sqrt{\rho_{SSD} + \rho_{GND}} - k_3\left(\frac{\dot{\varepsilon}^p}{\dot{\varepsilon}_0}\right)^{-\frac{1}{n_0}}\rho_{SSD} - \left(\frac{d_c}{d}\right)^2\rho_{SSD}\right)$$



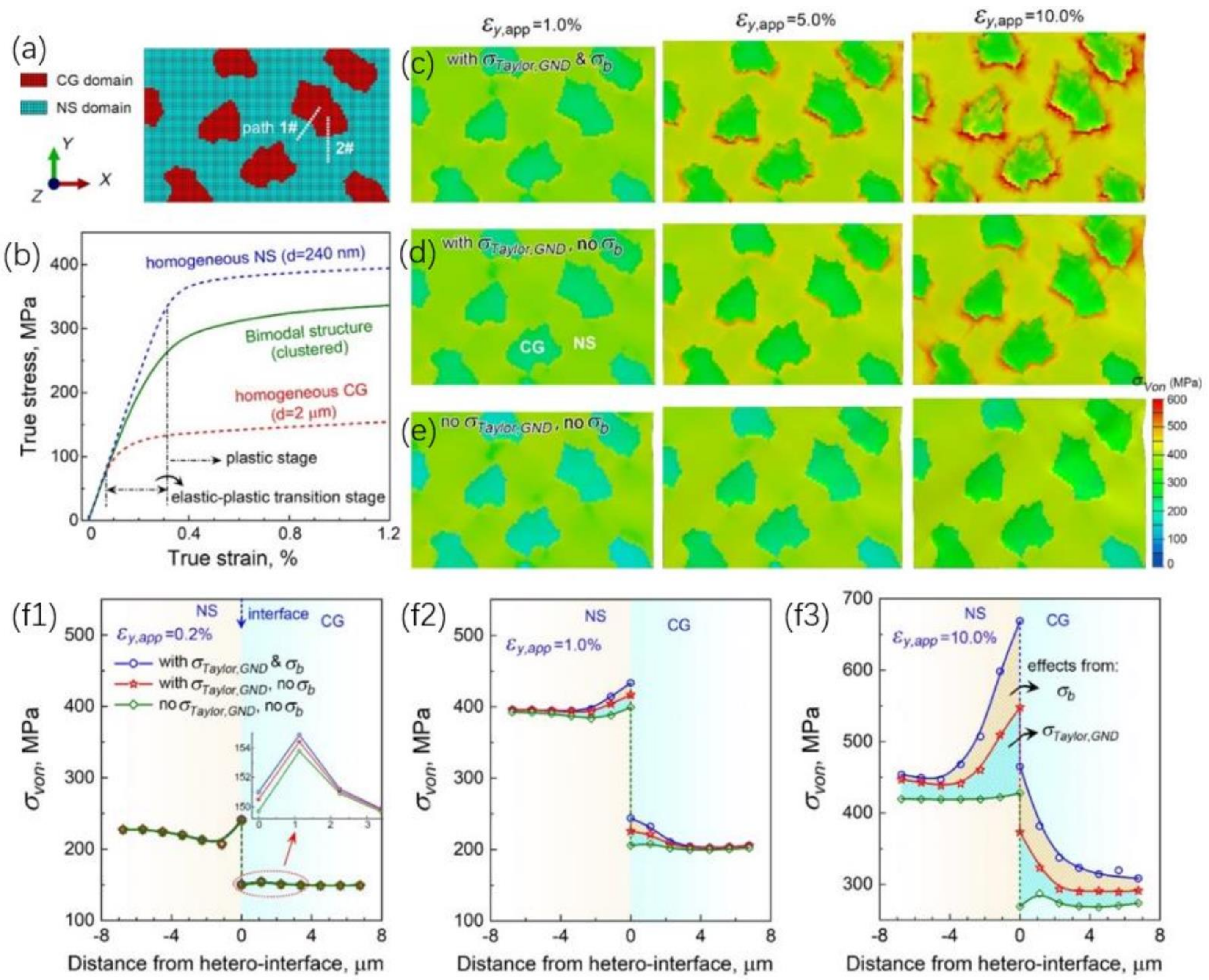
# Result

## ◻ Stress near domain boundary

Stress-strain curve of elastic-plastic transition stage (b) of the bimodal structure (a).

Mises stress at different applied strain, with short and long range effect of GND separated (c-e).

Detailed relation of Mises stress and distance from the hetero-interface at different applied strain (f).



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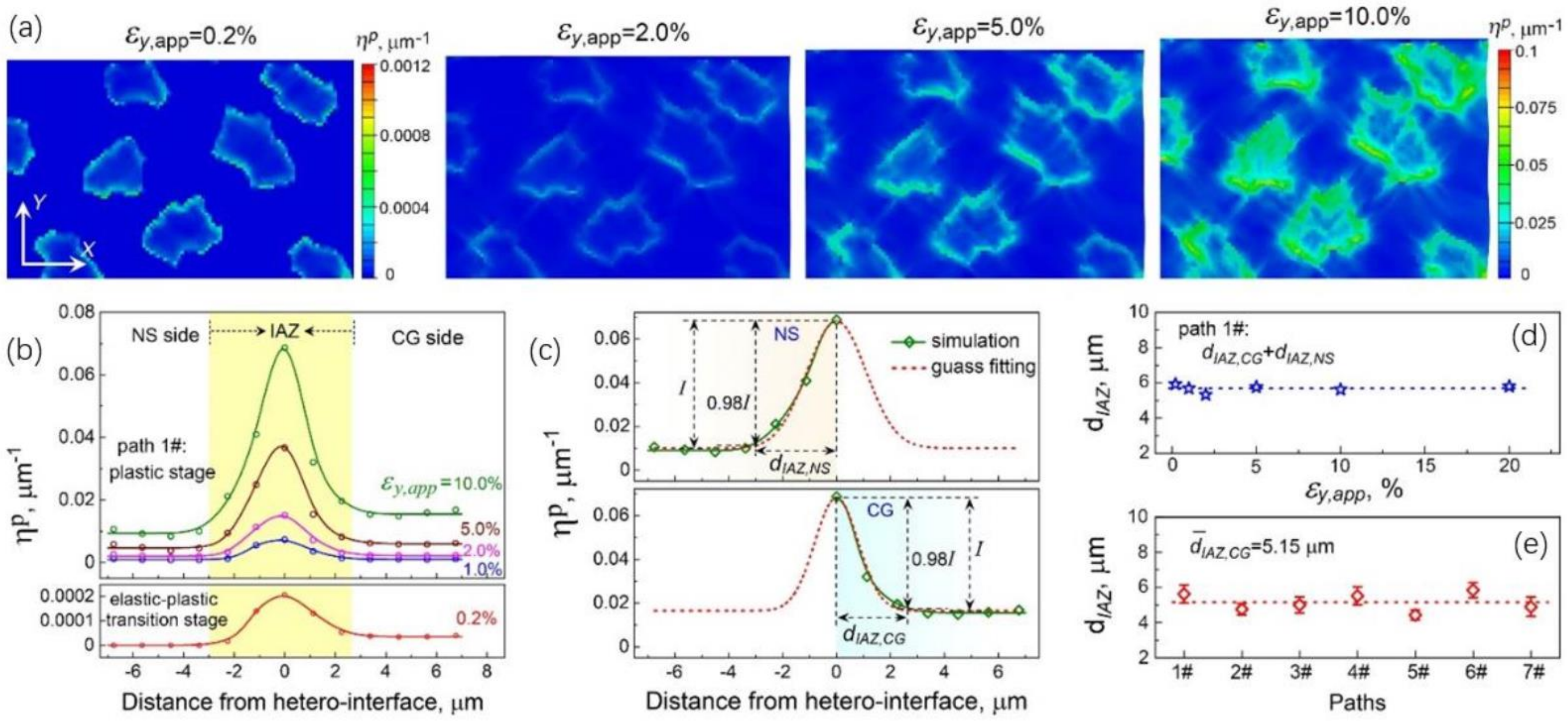
# ◻ Effective strain gradient near domain boundary

Strain gradient distribution (a) and relation with distance from hetero-interface, and definition of interface affected zone (IAZ) (b,c)

$d_{IAZ}$ of different loads and paths (d, e)




$d_{IAZ}$ nearly independent with load (and its direction), with a width around 5um (strain gradient characteristic length ~10um)

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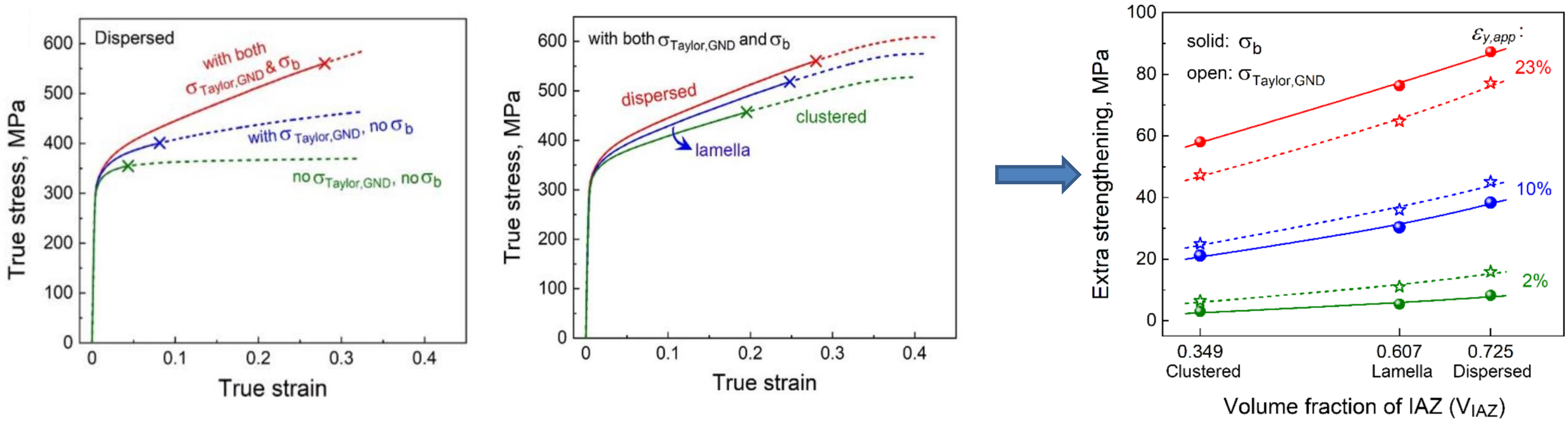
# ☐ Extra hardening of IAZ




Separate the effect of short/long range effect of GND, and compare the stress difference of the three bimodal structure

Nearly linear relations between extra hardening and the volume fraction of IAZ
---- effect from IAZ composed of the most proportion of extra hardening

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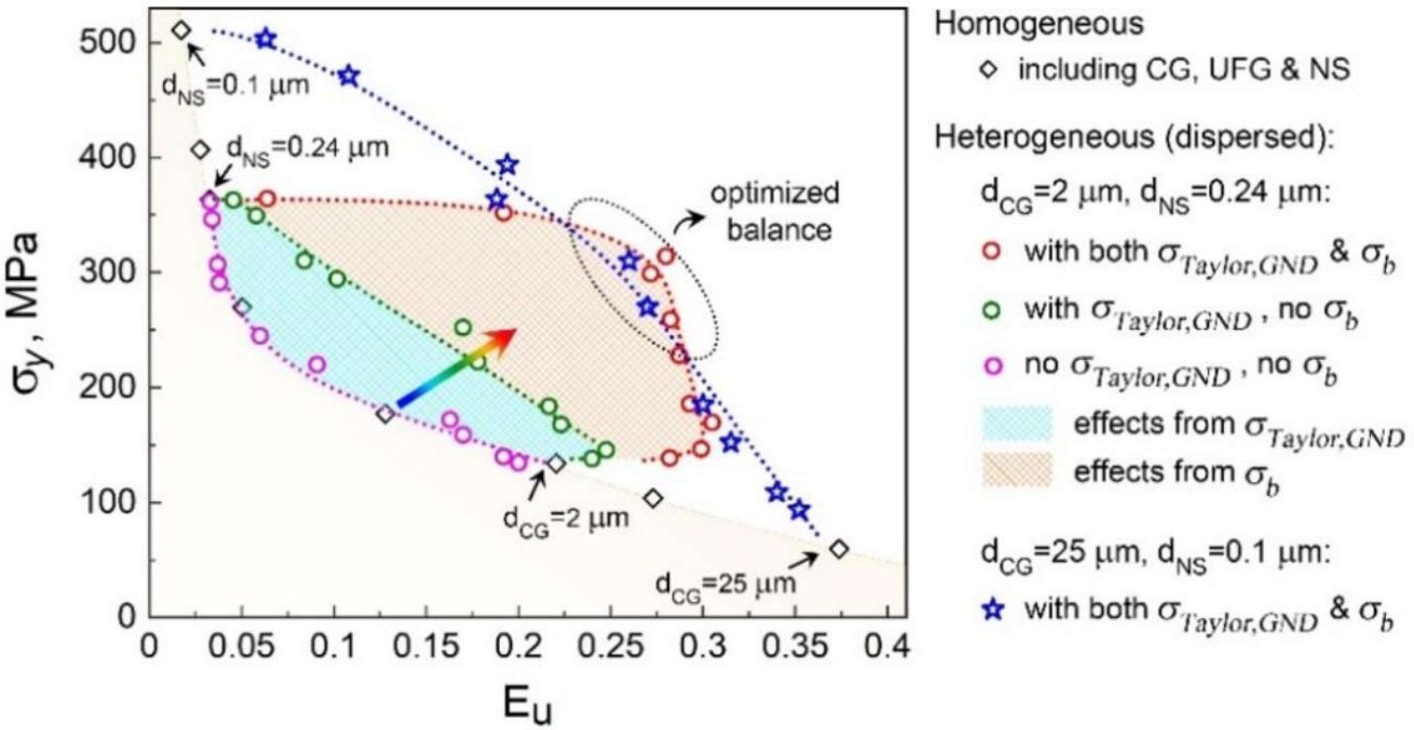
## Strength and ductility relations

Homogeneous materials, or macroscale heterogeneous materials (namely when the effect of GND is ignorable) have conventional relationships between strength and ductility.

Size effect allows extra strength/ductility

More extensive difference between heterostructure phases makes this extra property more significant.

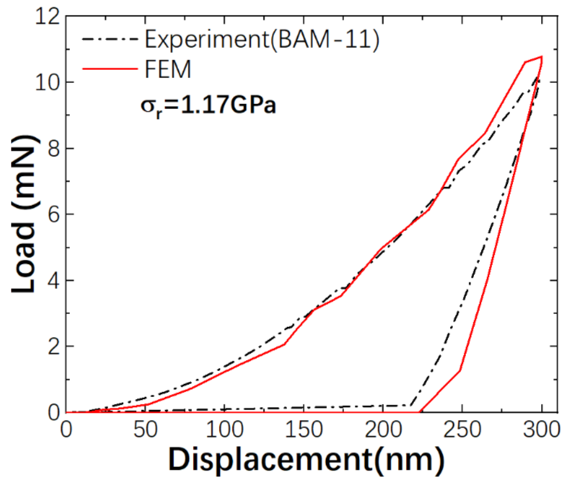



Optimization balance due to a maximum density of GND, where the generation and distinguish of GND reach balance.

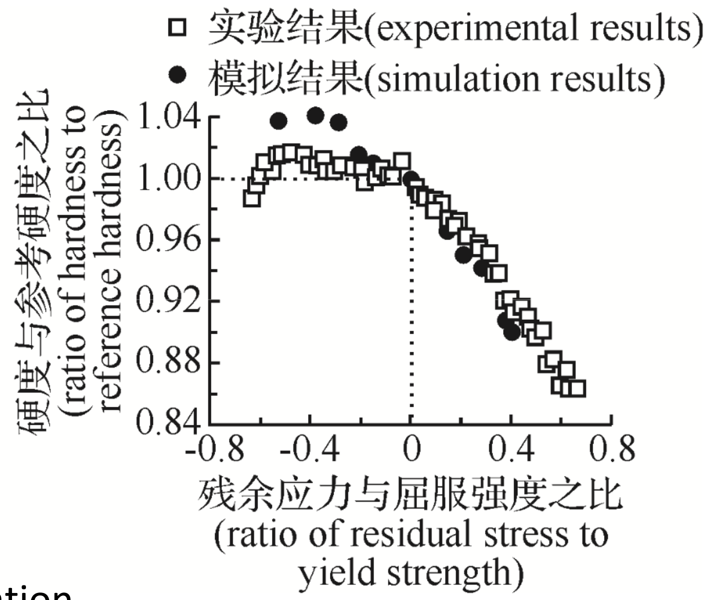
# Prospect

□ Structural Integrity, from aspect of residual stress

$$\sigma_r = A\mu b\sqrt{\rho^{r}_{GND}} \qquad \rho_{GND} = \rho^{r}_{GND} + \rho_G \qquad \sigma_{flow} = \sigma_y\sqrt{f^2(\varepsilon^p) + l\eta^p} + A\mu b\sqrt{\rho^{r}_{GND}}$$

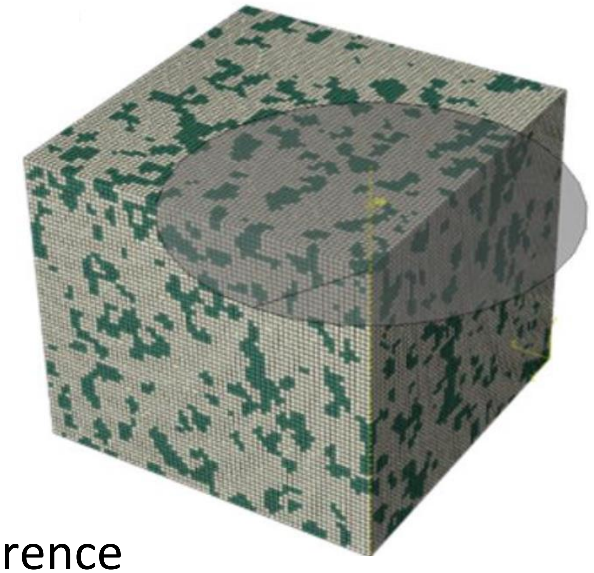



$\sigma_r = 1.17$Pa




Load-displacement curve, and relation between hardness and residual stress, Bu, 2020

BAM11 的纳米压痕硬度数据 (nanoindentation hardness data for BAM11)



Next Stage

Literature reference

→ 304Steel & Al alloy

# Prospect

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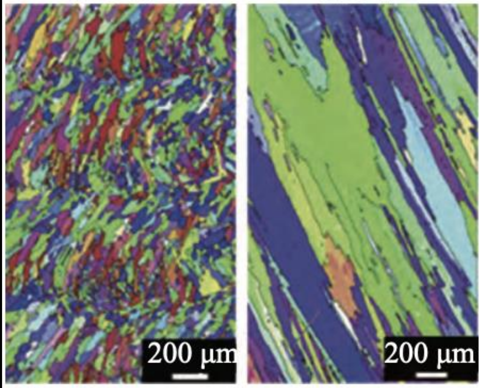
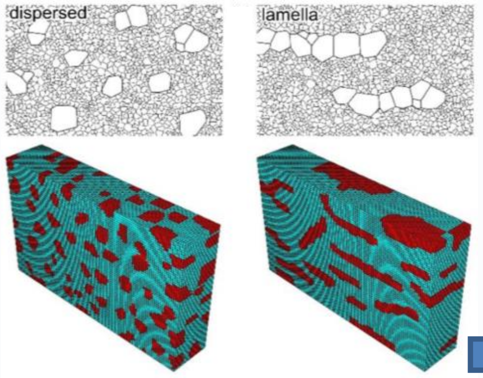
## ☐ Linking 3D printing, microstructure, mechanical feature, and application

Table 1 Grain size of selective laser melted 316L samples in different references

| Author and reference | Power / W | Scanning speed / (mm·s⁻¹) | Aspect ratio | Grain width / μm | Grain length / μm |
|---|---|---|---|---|---|
| Shamsujjoha, et al. | 400 | – | – | – | 200 |
| Montero-Sistiaga, et al. | 400 | – | 1.4 | 70 | 100 |
| Montero-Sistiaga, et al. | 1000 | – | 10 | ~100 | ~1000 |
| Sun, et al. | 380 | – | – | 13.2 | – |
| Sun, et al. | 950 | – | – | 11.6 | – |
| Ma, et al. | 200–2000 | 800–2200 | 5–15 | 16–27 | 120–400 |
| Wang, et al. (concept) | 150–350 | 700–1700 | – | 45 | – |
| Wang, et al. (Fraunhofer) | 296–353 | 150–225 | – | 20 | – |
| Voisin, et al. | 150 | 700 | – | 9 | – |
| Salman, et al. | 175 | 688 | – | 45 | – |
| Chen, et al. | 200 | 850 | – | 5.9 | – |
| Sistiaga, et al. | – | – | – | – | 100 |
| Saeidi, et al. | 195 | 800 | – | – | 10–100 |
| Jiang, et al. | 206 | 900 | 1.6 | 41.2 | 67.9 |
| Khodabakhshi, et al. | – | – | – | 7.5 | – |



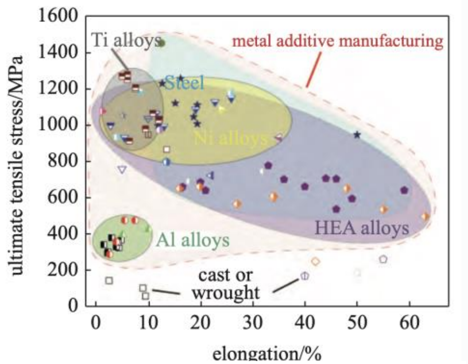

**Printing parameter and microstructure**

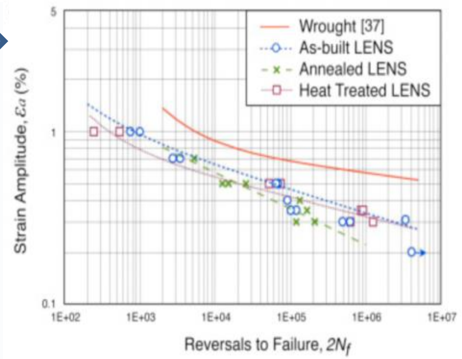



$$\sigma_{flow} = \sigma_Y + M\alpha\mu b\sqrt{\rho_{SSD} + \rho_{GND}} + \sigma_b$$

$$\sigma_{flow} = \sigma_y\sqrt{f^2(\varepsilon^p) + l\eta^p} + A\mu b\sqrt{\rho^r_{GND}}$$

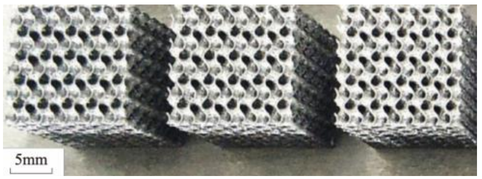
**Mechanism of heterostructure and residual stress**

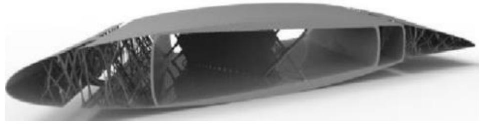


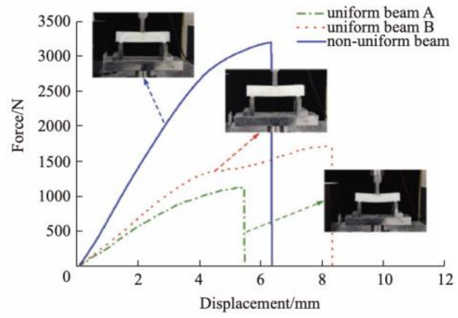




**Uniaxial property and fatigue property**

FUTURE WORK






**Aeronautical structure and structural property**

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